Optical design and Initial Results from The National Institute of Standards and Technology's AMMT/TEMPS Facility

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ABSTRACT

The National Institute of Standards and Technology's (NIST) Physical Measurement and Engineering Laboratories are jointly developing the Additive Manufacturing Measurement Testbed (AMMT)/ Temperature and Emittance of Melts, Powders and Solids (TEMPS) facilities. These facilities will be co-located on an open architecture laser-based powder bed fusion system allowing users full access to the system's operation parameters. This will provide users with access to machine-independent monitoring and control of the powder bed fusion process.

In this paper there will be emphasis on the AMMT, which incorporates in-line visible light collection optics for monitoring and feedback control of the powder bed fusion process. We shall present an overview of the AMMT/TEMPS program and its goals. The optical and mechanical design of the open architecture powder-bed fusion system and the AMMT will also be described. In addition, preliminary measurement results from the system along with the current status of the system will be described.

Keywords: Powder bed fusion, Additive manufacturing, selective laser melting, 3D printing, Radiometry

1. INTRODUCTION

Laser-based powder-bed fusion (LPBF) and other types of additive manufacturing are enabling more and more flexibility for industry and its end users to develop custom parts in-house for both research and production. The process does not require dedicated tooling and provides more possibilities than traditional subtractive machining by facilitating the manufacturing of nested structures, light-weighted assemblies and parts with complex internal geometries. The Powder-bed fusion manufacturing process has some challenges though. The process is not fully understood and the part yield can be affected by many of the process parameters including laser power, scan speed, layer thickness and hatching parameters.

NIST plans to address some of these challenges by developing an open platform testbed for laser-based powder-bed fusion system. The system will contain the Additive Manufacturing Measurement Testbed (AMMT)/ Temperature and Emittance of Melts, Powders and Solids (TEMPS) facilities. These co-located systems will provide a platform that allows full control of laser illumination including spot size, and power as well as the scan parameters like scan speed and hatch parameters. The AMMT is a process monitoring suite which observes the melt pool via co-axial detectors and an imager. Monitor signals are processed real-time with a field-programmable gate array (FPGA) and can be used to provide feedback control of the process parameters. TEMPS uses the testbed for heating samples to temperature for reflectance and emissivity measurements expanding NIST's existing emissivity measurement capability.

1.1 AMMT

The overarching goal of the AMMT is to research current and future in-situ measurement and monitoring methods to enable process control and rapid part qualification in LPBF systems. Multiple sensor systems will be incorporated which align co-axially with the laser and/or monitor the build bed from stationary position, similar to the R&D developments appearing in commercial monitoring systems [1]. However, additional platforms for expanded sensor placement allow research into new monitoring methods in addition to full control and definition of build variables such as power, speed, scan strategy, and environment conditions.

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Despite the rapid advances in commercial LPBF technology, much improvement may still be gained through fundamental studies such as process mapping, and testing new parameter spaces and scan strategies. Sensor system development with the AMMT will define required sensitivity, spectral and temporal bandwidth requirements for observing specific process phenomena, and primarily focus on optical methods such as high speed imager and photodetectors. These sensors will be used to measure observable phenomena related to part quality or specific defects. These fundamental studies, enabled through a flexible testbed, can not only improve the LPBF build process, but provide the measurement science for future in-situ part qualification.

Based on data obtained from fundamental studies, real-time control methodologies and algorithms may be developed. First, this data can support system identification for basic control strategies or reduced-order models for model predictive control. The AMMT will provide the hardware and software capabilities for in-situ defect or fault detection and handling (e.g., once-per-layer corrective action), or high-speed feedback control of laser power and velocity. Successful application of feedback control will provide the additional improvements unattainable through optimized process parameters and build strategies. Apart from these goals, the AMMT system will provide a means for development, testing, and demonstration of standard methods developed for other manufacturing processes measuring motion and geometric error through machine tool metrology principles [2], and open numerical control protocols such as G-code (RS-274) [3].

1.2 TEMPS

The NIST Sensor Science Division of the Physical Measurement Laboratory is responsible for advancing the measurement science, standards, and applications for sensing optical power, temperature, humidity, pressure, vacuum, flow, and related physical phenomena to support U.S. industry and trade. The Temperature and Emittance of Melts, Powders and Solids (TEMPS) facility utilizes the AMMT's build area not for additive manufacturing but for the production of high temperature samples for temperature and emittance measurements. Laser heating provides a vehicle to heat samples in both solid and liquid phases as well as observe the transition phase. The goal is to provide a capability of measuring materials in the 1000 K to 3000 K range.

Although TEMPS cannot be used during the additive manufacturing process in the course of AMMT operations (due to the optical configuration of TEMPS described below), it can be used to simulate the conditions during the additive manufacturing process. This provides valuable reflectance, emissivity and temperature data for materials used in additive manufacturing for modeling and fundamental research into the process. The flexibility of AMMT/TEMPS and its open platform nature provide users with the capability to modify a variety of parameters to gain knowledge of the process. Research of this type is limited on commercial LBPF systems due to restrictions of use and canned operating parameters within the systems.

TEMPS is not limited to measurement of powders, but can also utilize an in-situ heated sample holder to perform measurements on solid and bulk materials. Moreover, TEMPS has a retractable reflectometer, calibration sources and reflectance standards situated within the process chamber of the system to allow for transfer of calibrations from NIST's laboratory-based calibration facilities. These capabilities provide measurement potentials for not only additive manufacturing applications but other applications like directed energy deposition, high temperature materials and remote temperature measurement to name a few.

1.3 System architecture

The process of powder-bed fusion has been described in detail in numerous locations [4], so only a brief overview of the process will be provided here. The process begins with a build area filled with a flat thin layer of powdered material. Portions of the powder are then selectively fused to build a single layer of a part. This fusing is done in the AMMT/TEMPS system with a focused 500 W fiber laser beam scanned across the powdered material. The build area is then lowered and a new thin layer of powder is deposited over the previous layer. The new top layer is then selectively fused just as the previous layer. This process is repeated until the part is complete, providing a 3-dimensional part made of the fused powder material. The AMMT/TEMPS project requires the control and monitoring of several key parameters of this process including: laser power, scan speed, powder layer thickness, laser spot size, hatching pattern as well as access to the build area in order to monitor the process. For these reasons NIST is developing the AMMT/TEMPS powder-bed fusion system in-house.

The AMMT/TEMPS system is a product of collaboration between NIST's Engineering Laboratory and Physical Measurement Laboratory. A concept diagram is shown in Figure 1. The system uses a fiber laser guided by a 3D

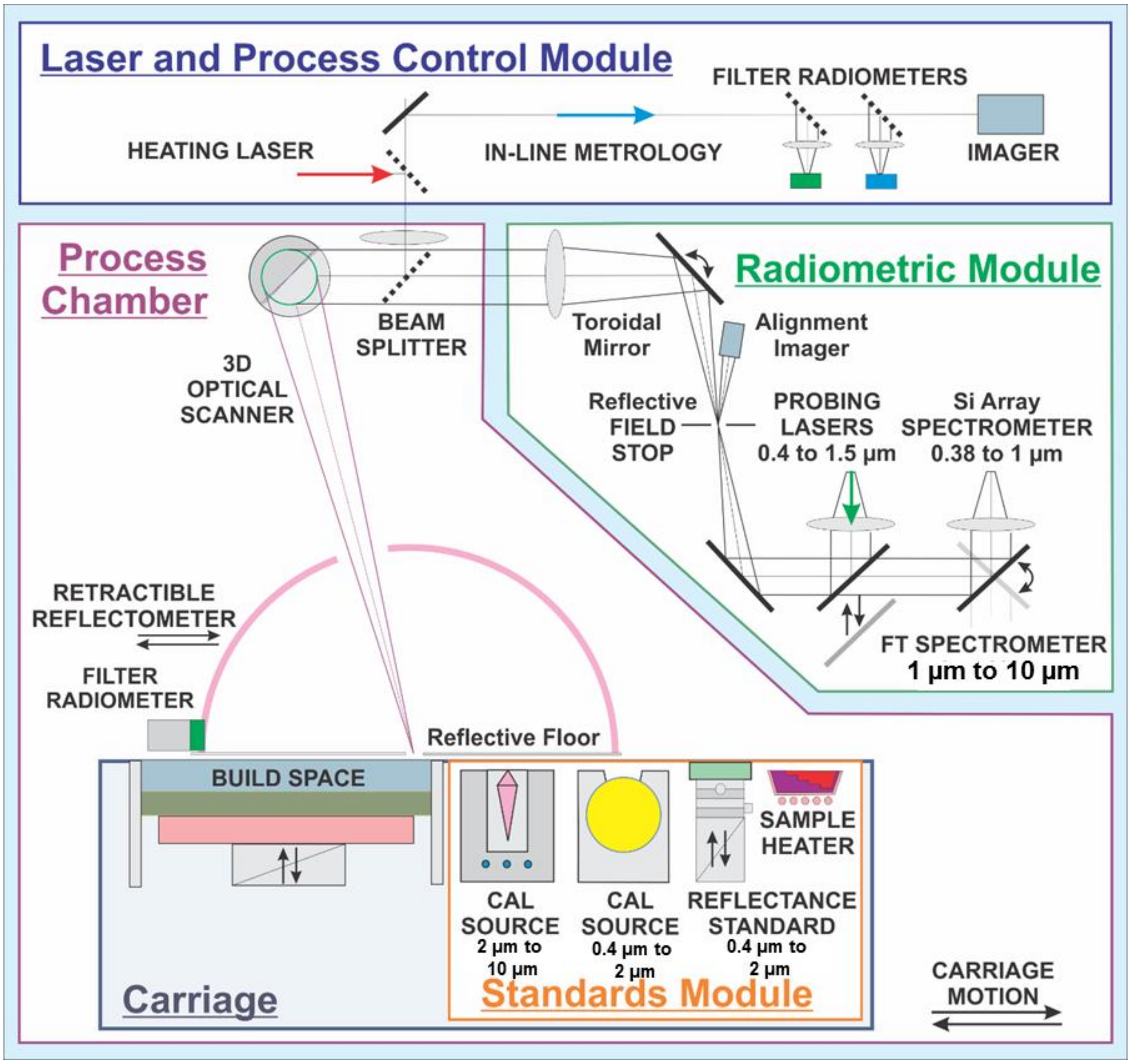

Figure 1:TEMPS/AMMT system architecture diagram.

optical scanner to produce heating over a 100 mm by 100 mm build area. The optical scanner, build area, powder management and sample motion is contained within a 1750 mm x 1200 mm x 780 mm sealed process chamber. The process chamber is evacuated and back-filled with Ar or N_2 gas to inhibit sample oxidation during heating. Light produced by the hot sample is relayed back through the *XY* scanner and either transmitted or reflected by a beamsplitter. The reflected light is further filtered to remove the fundamental laser radiation from the emitted radiation which is sent into the in-line process monitor comprised of filtered detectors and a high-speed imager. This in-line process monitoring is the heart of the AMMT system. The data from the high-speed detector and imager are collected and processed by an FPGA to provide real-time monitoring of the melt pool. This same FPGA also controls the scanner motions and the laser power to provide a feedback mechanism to enable process optimization. In-line monitoring can be coupled with other monitors, which can observe the melt pool from within the process chamber. In addition, the sample holder can be moved out of the scanner field so off-line normal incidence imaging can be done between build layers.

Light produced by the sample which is transmitted through the beamsplitter described above will be relayed into the TEMPS system by a toroidal mirror. A reflective field stop is used to limit the field-of-view of the TEMPS diagnostics while also providing alignment imaging and observation of the sample. Light transmitted through the field stop is relayed to suite of diagnostics including filtered radiometers, a Fourier Transform Spectrometer and array spectrometer for temperature measurements of the sample. The TEMPS system also incorporates a retractable hemispherical reflectometer for in-situ reflectance measurements which are required for accurate emissivity measurements. A more detailed description of the TEMPS system is provided in [4].

2. OPTICAL DESIGN

The optical train is shared by the fiber laser, TEMPS and the AMMT portions of the facility so the task of optical design of the AMMT/TEMPS system requires attention to both high laser power and the broadband performance requirements for both TEMPS and process monitoring. The goal is to operate TEMPS from approximately 400 nm to 10 µm in wavelength, and the AMMT's in-line process monitoring requires multiple visible and near infrared wavelengths to support multiple signal channels. To meet these requirements, the mirrors in the optical scanner and TEMPS, as well as the mirrors in the laser path leading up to the process monitoring beamsplitter, are coated with protected silver.

It was also decided the system would not use an *f*-theta type focusing lens in order to facilitate the wavelength range requirements. This allows the fiber laser and the TEMPS facility to use different optics for focusing or imaging by putting a beamsplitter prior to the *XY* scanner. The TEMPS requirement of operation out to 10 µm in wavelength also limits the selection of window materials for protecting the optical scanner optics from contamination due to laser interaction with the sample to specialized, cost-prohibitive materials such as BaF. Therefore, a 'disposable' folding mirror was added to the design to eliminate a line-of-sight path from the sample to the optical scanner to facilitate operation without a protective window. In this section, the optical design of the fiber laser delivery path and TEMPS is presented.

2.1 Laser delivery path

The laser incorporated in the system is a 500 W Continuous wave (CW) multimode Yb fiber laser operating at approximately 1070 nm wavelength with a 50 µm diameter output fiber. Modeling was done utilizing Zemax ray tracing software [6]. A diagram of the ray tracing path is shown in Figure 2. The output of the fiber laser is collimated with a 60 mm focal length collimator and modeled with a beam diameter of approximately 8 mm (FWHM) based on manufacturer's specifications. For simplification, the source was modeled as a 50 µm diameter uniform source and the collimator modeled as an ideal lens. The collimated light is sent through a plano-concave fused silica singlet lens with a focal length of -170 mm. This lens is mounted on a galvanometer-based linear translation stage that adjusts position based upon the scanner positons to maintain a tight focus in the build plane (a process commonly referred to as flat-fielding). This lens can also be translated on larger scale to provide a means of controlling the beam size at the sample by moving the focus of the system beyond the sample or build plane. Approximately 420 mm further along the beam path a 300 mm focal length air-spaced doublet (designed for focusing 1064 nm and 632 nm light) is used to focus the laser light. Both the doublet and the singlet are commercially available components.

The 45° angle of incidence beamsplitter which reflects the laser and separates the laser delivery path and the TEMPS optical path lies next in the optical train. This beamsplitter is an element that can be freely removed and replaced based on the requirements of the experiment. When TEMPS is to be used, the beamsplitter will be a high reflector at 1070 nm with a substrate and rear-side anti-reflection coating appropriate for the wavelengths of interest. When the AMMT is in use, the beamsplitter will be a broadband reflector to support both the laser wavelength and AMMT's individual monitor channels. Light reflected by the beamsplitter is transmitted through a 50 mm clear aperture optical scanner with protected silver coatings on SiC substrates. The scanner is galvanometer-based open frame model allowing it to be mounted in close proximity to the beamsplitter and folding mirror.

The final optic in the optical train is the folding mirror which blocks line of sight from the sample to the optical scanner. The focusing doublet, beamsplitter, optical scanner are contained within a supplemental chamber (called the scanner tower) mounted on top of the process chamber. The beamsplitter and folding mirror are mounted within the assembly such that they can be readily removed and adjusted in-situ to provide users with the capability to rapidly swap out these components as needed.

2.2 Optical configuration for TEMPS

TEMPS utilizes the same folding mirror, optical scanner and beamsplitter as described in section 2.1, however the direction of the light is opposite to that of the laser delivery path. TEMPS is designed to collect and form a nominal 1:1 image with the light generated by the laser-heated sample in the build plane in order to measure both sample emittance and reflectance for temperature measurements. As stated above, the beamsplitter reflects the fundamental laser light and

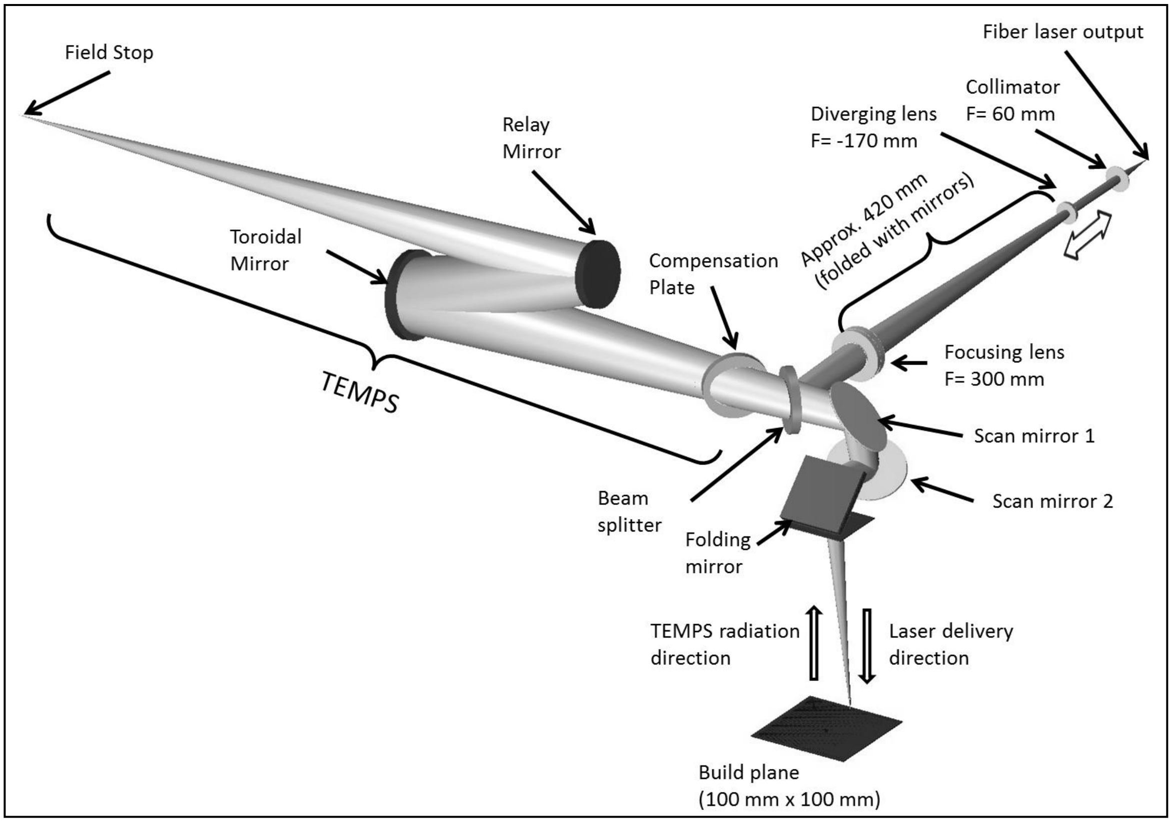

Figure 2: Raytracing diagram of laser delivery path and TEMPS.

transmits wavelengths of interest into the TEMPS section. This puts constraints on the beamsplitter and will require frequent replacement and removal as applications warrant specific transmission and reflection performance.

Looking at the TEMPS beam path in Figure 2, one can see that light passing through the beamsplitter subsequently passes through a compensation plate (CP). The CP is an antireflection coated optical flat whose substrate is identical to that of the beamsplitter. The CP is necessary to compensate for transverse chromatic aberration caused by transmission through the 45 ° tilted beamsplitter. The CP is also tilted about its vertical axis, but in the opposite direction thus providing a lateral chromatic shift in an opposite direction as that produced by the beamsplitter's substrate. The compensation plate also serves as an O-ring sealed window for isolating the process chamber.

Light transmitted through the CP impinges onto a 100 mm diameter, 500 mm focal length protected silver-coated toroidal mirror operating at a 10 ° angle of incidence. The mirror's tangential radius of curvature is adjusted in order to compensate for the optic's pitch angle as well as astigmatism produced by transmission through the tilted CP and beamsplitter. Light reflected from the toroidal mirror is relayed towards the TEMPS metrology suite with a protected silver-coated flat mirror operating at a 10 degree angle of incidence. The field stop of the metrology suite (pictured in Figure 1 in the real-time imaging module) is a reflective aperture wheel which is operated at an off-normal angle to allow for reflected light to be used for in-situ optical alignment.

The broadband nature of the TEMPS system requires the use of reflective imaging and collection optics and unlike the laser delivery path; TEMPS cannot use a linearly translating lens to maintain focus over the full 100 mm square build plane. This limits the useable area of the build plane to points which lie at an equal optical path distance from the toroidal mirror as the primary focus in the build plane. Placing the toroidal mirror such that it is in focus at an edge of the 100 mm square build plane allows for a nominal 100 mm diameter circular path that can be created by the 2D scanner, to be in focus for the TEMPS toroidal optical system. This path can be exactly calculated with ray tracing and is referred to as the metrology path for TEMPS. By incorporating a portion of this path along with linear translation of the build plane powder bed, the full length of the available powder bed can be used for long integration times during emissivity and reflectance measurements with TEMPS.

2.3 Optical configuration for AMMT

The AMMT utilizes light generated by the melt pool created in the build plane to observe the melting process during a LPBF operation. The light is broadband radiation generated by the high temperature of the melted metal powder. The AMMT's detectors lie just within the laser module and are separated from the laser delivery path with a beam splitter (shown in Figure 1) placed between the laser collimator and the translating diverging lens. The beam splitter reflects the light from the laser light and transmits wavelengths from about 950 nm to 400 nm. This allows for short wavelength light to be transmitted into the AMMT's detectors and imager.

Light is filtered off into 3 channels using beam splitters and sent into 2 detectors and a CMOS imager utilizing a 150 mm focal length achromat optimized for operation near 800 nm. The signals of these instruments are recorded with FPGA-based analog to digital electronics board and image processing module for high-speed data acquisition and analysis in order to achieve real-time monitoring of the process. This monitoring data can be used to produce feedback control of laser power, scan speed and laser spot size to control melt pool size and shape during the build.

The current laser delivery path is optimized for operation at the laser wavelength of 1070 nm. This means the focusing and diverging lens pair is not optimized for wavelengths shorter than 950 nm and thus the AMMT will be subject to chromatic aberrations from the two refractors in the laser delivery path. The latter affects the coupling efficiency of the channels and image quality of the AMMT. In order to achieve diffraction limited performance with the AMMT's imager, the bandwidth must be restricted to approximately +/- 10 nm centered at 800 nm. There are plans to design custom lenses for the laser delivery path which optimize both operation at the laser wavelength and the 800 nm region in order to increase the signal level and image quality in the AMMT imaging system. Furthermore, there are plans to incorporate additional light sources (LED or laser diode) within the process chamber to illuminate the build field to aid in the AMMT's imaging as well as other imagers in the process chamber.

3. RESULTS OF PRELIMINARY LASER TESTING

The models generated by ray tracing provide a prediction of system performance, but testing components and configurations on the bench can provide a more accurate indication of final system performance. For this reason, several tests were performed with the laser and proposed optical hardware in order to determine the final performance of the system. Furthermore, results of these experiments can provide data regarding performance limitations of components that cannot be determined by ray tracing alone. Tests were conducted with the optical components on a traditional optical bench for ease of alignment and manipulation and included temporal switching, laser spot size and thermal loading measurements.

In the experimental setup the collimated output of the laser was sent through the diverging lens and focusing lens used in the final configuration. An anti-reflection coated fused silica glass wedge was inserted in the path of the converging beam to generate a pair of reflected beams which were attenuated to approximately 1% of the input beam's power. The transmitted beam was sent into an air-cooled beam dump and the attenuated beams were directed through absorbing neutral density filters to further attenuate the beams and into a high speed array sensor and a Si-based photodetector respectively. The neutral density filters were chosen based on signal levels in order to prevent saturation of the CMOS sensor and photodetector.

The laser used in the AMMT/TEMPS system is a CW fiber laser, but through gating and modulation of the laser pump diodes the fiber laser's power can be gated on/off or adjusted at a high speed. Using the latter function, the laser was also gated at a rate of 20 Hz with a 250 µs pulse duration further reducing the average power of the laser to 0.5 % of the CW average power. Despite the gating the laser was seen to hit a steady state easily within the 250 µs window.

3.1 Temporal laser control

As stated, gating and modulation of the laser pump diodes which pump and control the fiber laser's power can be gated on/off at a high speed. Tests were done to measure the response time of the laser to power adjustment via analog voltage modulation and rise and fall times due to gating of the laser. A 1 µs rise and fall time time trigger pulse was used to gate the laser with a 250 µs (+/- 5 µs) duration to determine the switching response of the laser. Within the 250 µs pulse the laser achieved a steady state thus allowing for rise/fall time measurements. At 50% rated power the switch on time of

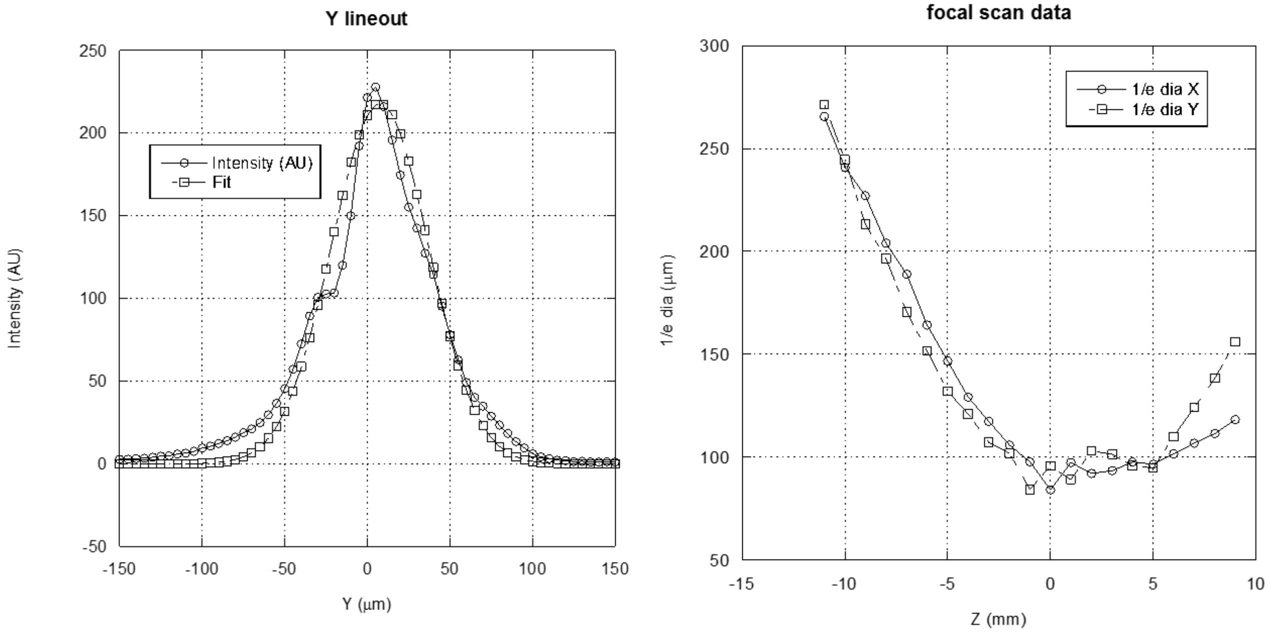

Figure 3: Results of laser spot size measurements.

the laser (5% to 95%) was recorded to be 57 µs (± 5 µs) with a fall time of 56 µs (± 5 µs). Similar results were seen over the full range of measurement of 30 % to 90 % nominal laser power level. [7]

3.2 Laser spot size measurements

As stated previously in section 2.1, the fiber laser used in the system is a multimode fiber laser with a 50 µm diameter output fiber and for modeling purposes the output beam was represented as a uniform flat top type beam. However, according to the manufacturer's specifications, the beam parameter product (BPP) is between 1 mm·mrad and 2 mm·mrad yielding a number of modes supported by the fiber ranges from 25 to 60 depending on the actual BPP. Such a low number of modes suggests that the beam profile at the exit of the 50 µm fiber may be significantly less uniform than the top hat profile that was modeled. In order to determine the actual laser profile at the focus of the system, the spot size was measured using the system described in the section 3 introduction. The results are shown in Figure 3.

The 2D images were recorded with a CMOS sensor with 5 µm pixel pitch during the steady state portion of the laser output within the gated pulse. Images were recorded using a 10 µs integration time and averaged over 500 samples. The graph on the left hand side of Figure 3 shows the vertical lineout of the smallest focal spot along with a Gaussian fit (dotted line). This plot shows that the spot more closely resembles a Gaussian profile than a flattop. However, the profile has a significant amount of structure from the multiple modes of the fiber.

The graph on the right hand side of Figure 3 shows the results of the Gaussian fits of the measured lineouts of the beam at the positon of the build plane versus the position of the diverging lens relative to the 300 mm focal length focusing lens. This indicates that the spot size is relatively insensitive to separation distance near the focus. The best focus occurs at about 0 mm on the plot and remains near 100 µm in diameter (1/e) for -2 mm to +5 mm (relative to position of smallest spot). This is believed to be due to the multimode fiber output. The plot also shows that the spot size can be increased by decreasing the separation between the diverging and focusing lens. This is consistent with the model and can be used to vary the spot size at the build plane should experiments require it.

3.3 Thermal load testing

The broadband nature of the AMMT/TEMPS facility requires the use of protected silver coatings on many of the optics in the laser delivery optical train. Protected silver coatings can provide reflectivity from about 400 nm to 20 µm in wavelength making the coating a good fit for a broadband application like that presented here. However, the performance of protected silver can vary by manufacturer [8]. Furthermore, protected silver coatings absorb approximately 2 % of the 1070 nm wavelength of the fiber laser. This can translate to as much as 10 W of laser power

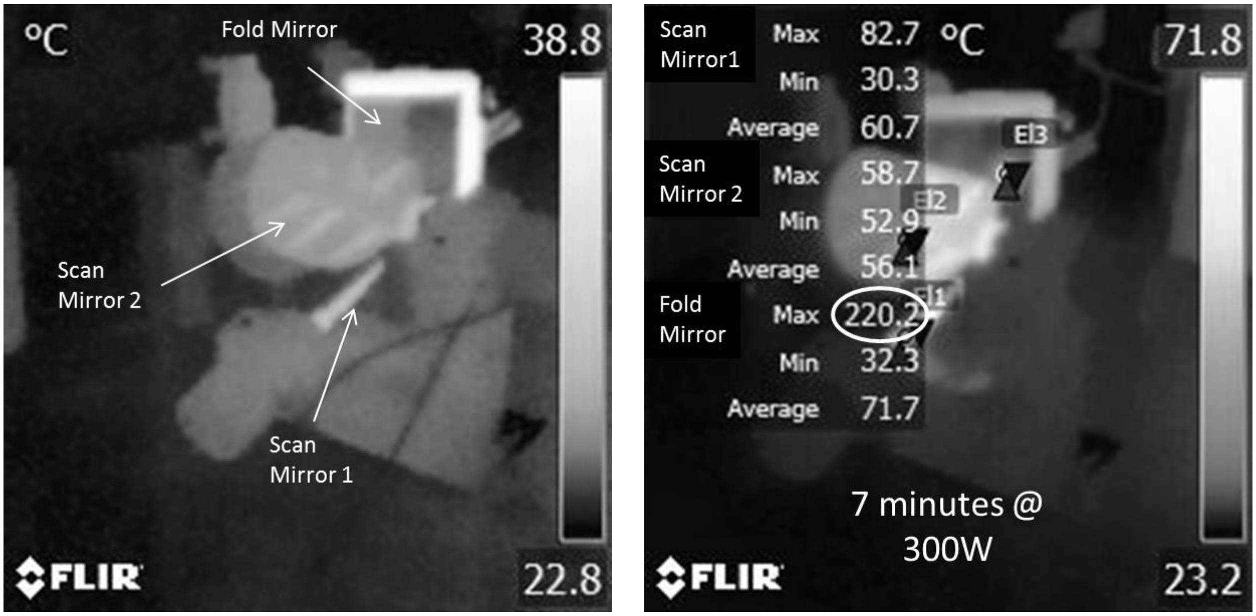

Figure 4: Images from thermal load testing of the protected silver mirrors.

being absorbed in a mirror. Ray trace modeling indicated that spot size on the mirror should be no smaller than 1 cm in diameter (FWHM) on the silver-coated optics. However, as shown in the previous section the beam distribution is closer to Gaussian than the flat top distribution used in the ray tracing model. Given these conditions it is necessary to verify performance of protected silver coated optics in the AMMT/TEMPS laser delivery path.

The thermal load testing was conducted using the final configuration of all of the optics including the reflective optical scanner and folding mirror. The laser was operated in CW mode in order to accurately load the optics in the beam path. The output of the laser was directed onto an air-cooled beam dump capable of absorbing 600 W of optical power. Testing was done using laser power settings of 40 %, 50 %, and 60 % with time durations of up to 10 min. with the scanner mirrors maintaining a static position. The temperature was recorded using a FLIR i7 [6] infrared camera at various intervals during exposure to the laser beam. The i7 was operated using an emissivity setting of 0.5.

Two recorded images are shown in Figure 4. The image on the left hand side shows the setup immediately before the 60 % power setting test. The image notes the position of scan mirror 1 (SiC substrate viewed edge on), scan mirror 2 (SiC substrate viewed form the back) and the fold mirror (fused silica substrate viewed from the front). The image on the right hand side of the figure shows the temperatures of the elements after 7 min. of exposure to 60 % power from the laser. The annotations in the image are done by FLIR image evaluation software. Mirror 1 of the scanner is the smaller of the 2 scanner mirrors and rises to a temperature of 82.7 °C and mirror 2 rises to a temperature of 58.7 °C. It should be noted from this image that the substrates of these mirrors appear to be heating up uniformly due to the high thermal conductivity of SiC. This is in contrast to the folding mirror which has a measured temperature of 220.2 °C and is only locally heated due to the fused silica substrate's significantly lower thermal conductivity (approximately 1 % of SiC). The result of this local heating was a failure of the folding mirror's protected silver coating. It should be noted that a more appropriate number for the emissivity of the fold mirror is about 0.03 which would increase the actual temperature to closer to 275 °C [9]. Subsequent to the conclusion of these tests the scanner mirrors were inspected and found to have incurred no damage during the test.

The results of these tests indicate that additional action needs to be taken to enhance the lifetime of the mirrors under high power laser operations. These include incorporating a Si substrate for the folding mirror of the system to improve heat removal from the optical coating and force air cooling of the scanner tower to help maintain lower mirror temperatures. In addition, it was also noted that the optical mount (anodized aluminum) of the folding mirror was also heating up during exposure. This is thought to be due to scatter and back reflections from the focusing lens that were observed during the testing and should be minimized by appropriate baffling in the final design.

4. CONCLUSIONS

In this paper NIST's effort to develop an open platform laser-based powder bed fusion system has been presented. The goals of the AMMT and TEMPS projects as well as an overview of the system architecture are disclosed. In addition, we presented the results of laser characterization and thermal loading tests of the optical components and lessons learned from these measurements. This is only the very beginning of the development of this facility. In the coming year the process chamber and the powder bed fusion system will be assembled and the full system will be commissioned. When available, the AMMT/TEMPS facility will provide valuable tool for the additive manufacturing community as well as provide a valuable tool for NIST's optical thermometry effort.

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